

**CONTROL SYSTEM UPGRADE FOR A MASS PROPERTY MEASUREMENT  
FACILITY**

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## **ABSTRACT**

The Mass Property Measurement Facility (MPMF) at the Goddard Space Flight Center has undergone modifications to ensure the safety of Flight Payloads and the measurement facility. The MPMF has been technically updated to improve reliability and increase the accuracy of the measurements. Modifications include the replacement of outdated electronics with a computer based software control system, the addition of a secondary gas supply in case of a catastrophic failure to the gas supply and a motor controlled emergency stopping feature instead of a hard stop.

## **INTRODUCTION**

The existing MPMF was purchased in the early 1970's. Many outdated discrete components in the system are no longer available from vendors. To date, the most serious problems caused by the outdated technology have been the malfunction of the data display register and relay contact failures. Interlocks in the MPMF control system use antiquated relay technology. Malfunction and failure rates of these relays have become unacceptable.

During a recent fault tree analysis several areas of operation were identified as potential hazards to the test item and MPMF. The existing system utilizes an emergency hard stop feature which, when activated, introduces undesirable inertial loads into the test item. This feature could structurally damage flight test items if either a sudden loss of gas pressure or moment overload condition is detected. Replacing the emergency hard stop feature with a motor controlled stop and secondary gas supply system mitigates this risk.

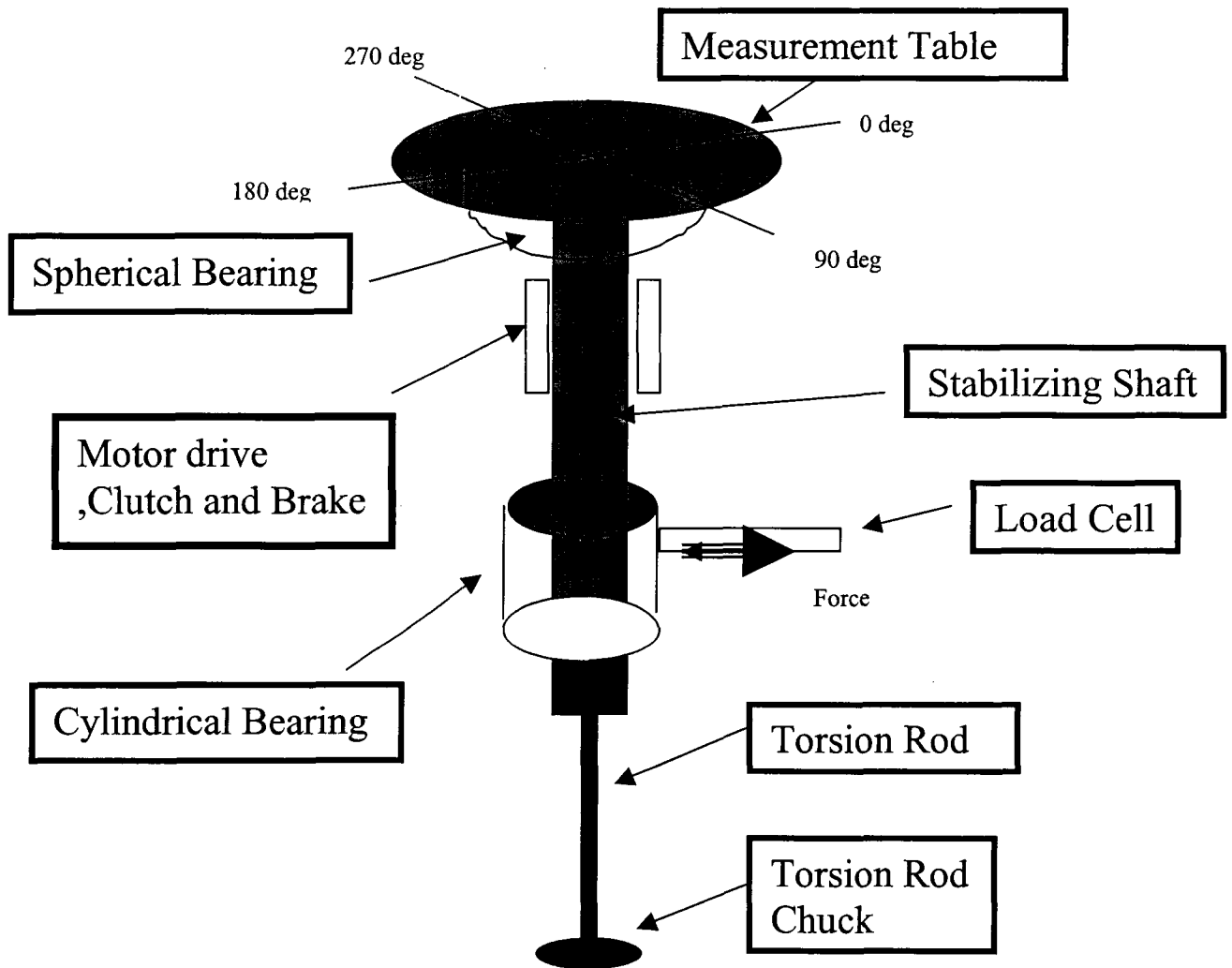
The old data acquisition process involved several steps that inherently introduce the possibility of human error.

- Data is displayed via LED registers on the console and are not saved electronically for later viewing or verification.
- These LED measurements are then copied to a paper datasheet by the console operator (introducing a potential read or copy error).
- The datasheet information is then copied into an excel spreadsheet by hand (again this introduces a potential copy error)

## MPMF FACILITY DESCRIPTION

The MPMF (Figure 1) consists of a spherical air bearing supporting a circular measurement table and the test item. Test items up to 10,000 lbs. are accommodated on the MPMF. A rigid stabilizing shaft is attached to the base of the spherical gas bearing and extends down through a lower cylindrical gas bearing.

The test item loads are reacted by the gimbaled spherical bearing. If the test item center of gravity is offset from the table center, the test item, table and spherical bearing will tilt. This angular displacement is reacted by the lower cylindrical bearing with a load cell to measure the moment unbalance.



**Figure 1. MPMF measurement system**

The entire table and support structure rests on a platform scale that is used to determine the test item weight. In the center of gravity mode the stabilizing shaft is free to rotate about its axis. The center of gravity (c.g.) measurements are performed by recording the moment (load cell force reading x distance down from table top) at each of the four quadrant table orientations (0 degrees, 90, 180 and 270 degrees). The c.g. distance from the 0-180 axis is calculated by dividing moment about the 0-180 axis by the test items weight. Similarly the c.g. distance from the 90-270 axis is determined by dividing the moment about the 90-270 axis by the test item weight.

## **MPMF BASIC OPERATION**

To measure moment of inertia, the MPMF employs a torsion rod. This slender rod is rigidly attached to the measurement table and extends down through the center of the stabilizing shaft. This torsion rod is used only in the MOI mode. In this mode the base of the torsion rod is fixed using a motorized chuck. The table is then manually rotated approximately 3.5 degrees and a piston is extended to hold the table displacement. The piston rod is then retracted and the table begins oscillating about the fixed lower torsion rod position. The table is now acting as an inverted torsional pendulum with the rotation restrained only by the torsional stiffness of the rod. This oscillation is basically undamped and frictionless (neglecting air drag).

A large optical pickup disc is positioned on the stabilizing shaft just above the lower cylindrical air bearing. Phototransducers sense light sources through slots and holes on this pickup disc. The slots are used for moment of inertia timing to measure the period of oscillation. The other holes featured in the pickup disc were designed to indicate table position and speed measurement. The time period is averaged over the number of oscillations that occur and is directly proportional to the moment of inertia.

Product of inertia can be calculated by driving the table to a selected rotational speed and measuring the moment in the same manner as the CG measurement. Moments are displayed for each speed selected by the operator as the rotating tabletop is slowed using a brake. By recording the moments at several speeds the engineer can separate the static and dynamic components of the imbalance.

The current moment measuring system consists of a strain gage type force transducer utilized as a moment sensor. The output of the sensor is a bipolar signal amplified by 27.6 db and routed to a voltage to frequency converter and digital counter. The converter and counter function together as an integrating digital voltmeter. The converter generates a signal with a frequency proportional to the output of the moment sensor. The counter totalizes this frequency and the resultant indication is a direct measurement of the system moment. The output is a convenient digital indication and has been integrated over a finite period, thereby averaging out noise and vibration.

## **MPMF Facility Upgrade Hardware Capabilities**

The modifications to the MPMF were designed to increase measurement accuracy and increase reliability. The new acquisition board purchased for this task is listed below

Acquisition board

16 bit 1 in 65,536

Max sampling rate is 333 KS/s

Clock Speed 20 MHz (a hardware controlled task will be executed in <50 ns.)

The areas of critical performance are 1) the precision in executing Indexing Ring signals and 2) Precision in acquisition of the Dynamic/Static moment forces. The indexing ring provides pulses synchronized to the spin table position. The accuracy in executing indexing ring signals is critical in measuring the period of oscillation for computing MOI, measuring the spin table speed and the timing of the moment force measurement acquisition for computing CG and POI.

The accuracy in acquisition of the Dynamic/Static moment forces is dependent on the acquisition board. This task affects the accuracy of the measurement of the moment force needed for computing CG and POI.

### **How the areas of critical performance affect MPMF operation**

#### **1) MOI Measurement**

The equation for computing MOI is:

$$I_o = T^2 K - I_t - W/gD^2 \quad (1)$$

Where:

$I_o$  = moment of inertia of test item about its centroid.

$T$  = period of oscillation

$K$  = constant for system involving elastic characteristics of torsion rod and  $(2\pi)^2$  factor.

$I_t$  = tare moment of inertia of machine, fixtures etc.

$W/g$  = mass of test item.

$D$  = center of gravity offset from axis of oscillation.

The period of oscillation ( $T$ ) is needed to compute MOI. This period is found by measuring the elapsed time between start and stop trigger pulses from the table indexing ring. The start pulse initiates a 100 KHz clock via hardware triggering on the acquisition board. The stop pulse stops the clock. This 100 KHz clock enables the nominal (2 sec) period of oscillation to be measured to 0.00001 sec. Using hardware triggering, a 20 MHz clock on the acquisition board enables the start and stop pulses to be initiated in < 50 ns.

## 2) POI Measurement

The equation used for computing POI is:

$$POI = \frac{(D - S) g}{\omega^2} \quad (2)$$

Where:

D = measured dynamic moment which includes the static moment

S = calculated static moment

$\omega$  = angular speed in radians /sec

g = acceleration of gravity

The variables needed to compute POI are D (measured dynamic moment which includes the static moment) and  $\omega$  (angular speed in radians per second). The dynamic and static moment force is measured by a load cell (force transducer). The acquisition board inputs the moment signal into the computer. The accuracy of the load cell and the resolution of the acquisition board determine the total accuracy of the dynamic/static moment force measurement.

### Load Cell

Rated Output	4.45 KN (1000 lbs)	3.39 KNm (30000 in-lbs)
Accuracy (0.25% of rated output)	11.1 N (2.5 lbs)	8.47 Nm (75 in-lbs)

### Acquisition Board

Resolution 16 Bit 1-65,536	0.066 N (0.015 lbs)	0.05 Nm (0.45 in-lbs)
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As shown above, the Acquisition Board resolution is sufficient to process the sensor data without diminishing accuracy.

The accuracy of the timing of the acquisition of the load cell data determines the accuracy of the moment angle measurement. The acquisition of the load cell data is obtained by the start and stop trigger pulses from the table indexing ring. The Start and Stop pulses begin and end the acquisition. Using hardware triggering, a 20MHz clock on the acquisition board enables the start and stop pulses to be initiated in  $< 50 \text{ ns}$  ( $5 \times 10^{-8} \text{ sec}$ ).

$$60 \text{ RPM} = 1 \text{ Rev/ sec} \quad (3)$$

$$1 \text{ Rev/sec} = 4.785 \text{ m/s (15.7 Ft/s) @ the 1.524 m (5 Ft) dia. Index Ring} \quad (4)$$

$$50 \text{ ns (} 5 \times 10^{-8} \text{ sec) @ 60 RPM} = 2.0 \times 10^{-8} \text{ m (} 7.87 \times 10^{-7} \text{ in.)} \quad (5)$$

The speed is obtained by measuring the elapsed time between start and stop trigger pulses from the table indexing ring. The Start pulse starts a 100 KHz clock via hardware

triggering on the acquisition board. The stop pulse via hardware triggering stops the clock. The 100 KHz clock enables the nominal (60 RPM) angular speed to be measured to within 0.00006 RPM. Using hardware triggering, a 20 MHz clock on the acquisition board enables the start and stop pulses to be initiated in < 50 ns.

## **REPLACEMENT OF EMERGENCY HARD STOP FEATURE WITH MOTOR CONTROLLED SLOWING AND SECONDARY GAS SUPPLY SYSTEM**

The MPMF upgrades increase the safety of flight payloads by removing an emergency hard stop feature and providing an emergency secondary gas supply system.

### Original System

The original system engaged a hard stop in the event of sudden primary gas supply pressure loss or a moment overload condition. Once any of these conditions are present the system would engage the frictional brake and bring the table rotational speed to zero within one revolution. A mechanical ring would then rise to support the upper spherical bearing and tabletop. Although this feature was originally designed to protect the bearing from seizing against the lower contact, this sudden stop generates a high torque on the spacecraft and could cause structural damage.

A payload spinning at 100 RPM when brought to a rotational speed of 0 within one revolution generates the following torsional G's as a function of radius out from the table center.

$$T_{\text{stop}} = \text{time to go from 100 rpm to 0 rpm} = \frac{1}{100 \text{ rev/min} \times 1 \text{ minute}/60 \text{ sec}} = 0.6 \text{ seconds} \quad (6)$$

Calculating tangential velocity of the table (at radius of 0.508 m (20 inches))

$$V_{\text{tan}} = 100 \text{ Rev/min} \times 1 \text{ min}/60 \text{ sec} \times 40 \text{ \Pi in}/1 \text{ rev} = 5.32 \text{ m/s (209.4 in/s)} \quad (7)$$

Calculating de-acceleration of table top

$$A_{\text{hard stop}} = V_{\text{tan}} / T_{\text{stop}} = 5.32 / 0.6 = 8.86 \text{ m/s}^2 (349 \text{ in/sec}^2) \quad (8)$$

$$\text{This is equivalent to } 8.86/9.81 = 0.9 \text{ G's} \quad (9)$$

Figure 2 below indicates what G levels are generated by a hard stop for payloads with structure positioned at a 1.27 m (50 in.) radius from the table center. Spacecraft with long antenna booms are particularly at risk during a hard stop scenario.

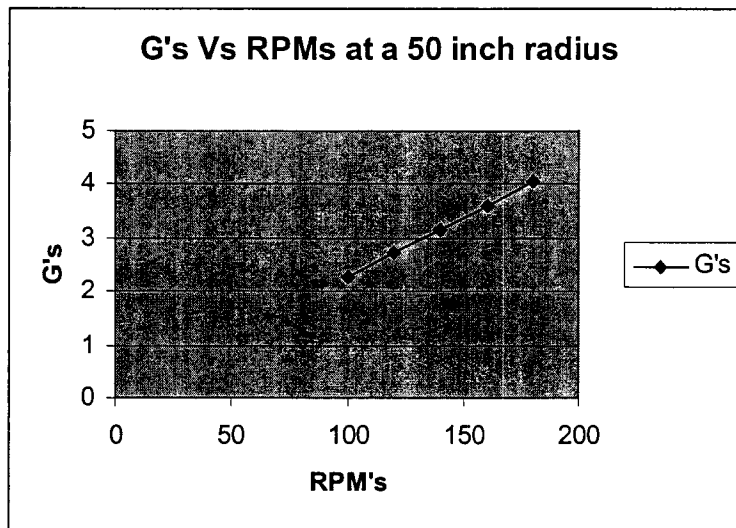


Figure 2. G's Vs. RPM's at a 1.27m radius

Even if the radius is significantly reduced, activating a hard stop generates undesirable inertial effects. As shown in Figure 3., spacecraft structure positioned 20 inches from the table center still must survive a significant G load.

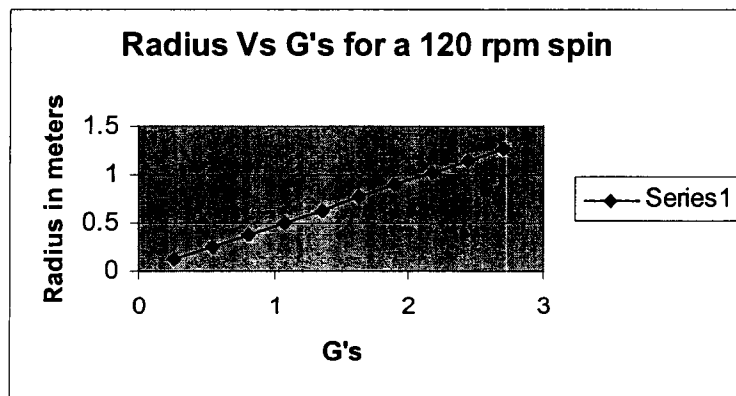


Figure 3. Radius Vs. G's at a 120 rpm spin

#### New System

To eliminate the need for an emergency hard stop feature a secondary gas supply system was incorporated into the new control system design. This new system senses a decrease in the primary gas supply system pressure and provides a secondary gas source to float the upper table until a controlled stop can be executed. This additional gas supply system provides up to 10 minutes of gas supply pressure needed while the motor controller is executing a controlled stop. A warning light and error indicator on the computer screen alert the operator that the secondary gas supply system has been activated and that the system will begin executing a controlled stop. A GN<sub>2</sub> bottle (N size) is mounted to the



new control system cabinet. The 15.2 MPa (2200 psi) supply pressure of this reservoir is reduced to 1.1 MPa (160 psi) using a regulator valve. A new pressure sensing regulator valve is installed down stream of both the facility gas and secondary gas supplies. When this valve senses pressures less than 690 KPa (100 psi), the secondary gas supply switch is opened allowing flow to the pressure sensing regulator valve. Supply gas flow continues through a filter, safety valve and flow meter into the upper and lower bearing regulator valves.

#### Motor Controlled Slowing

The old system executed an emergency stop by providing a maximum voltage to the clutch plates, causing the braking forces. The new system uses the motor for controlled slowing. The motor speed will be directly proportional to the input voltage to the controller. The field strength is variable to provide torque regulation of the motor. The output of the controller is the motor armature power. The controlled stop slows the measurement table in accordance with the rates selected at the beginning of the test. These deceleration rates will be selected by Code 549/ Project personnel before each POI test.

## **CONCLUSION**

By replacing the outdated control system with a computer based software control system accuracy and reliability improvements were realized. The modifications made to the MPMF have increased accuracy in the dynamic/ static moment force measurement, period of oscillation measurement, and timing of the indexing ring signals and data retrieval/ report generation. This new control system automatically stores and saves all data. POI data is plotted real time to aid the operator and project personnel in evaluating the data before the test item is reconfigured into the next test orientation. The addition of the secondary gas supply system and motor controlled stopping feature reduce potential risks to test item structural damage and facility bearing damage. These modifications avoid costly repairs associated with flight hardware replacement, facility spherical bearing replacement and facility down time.